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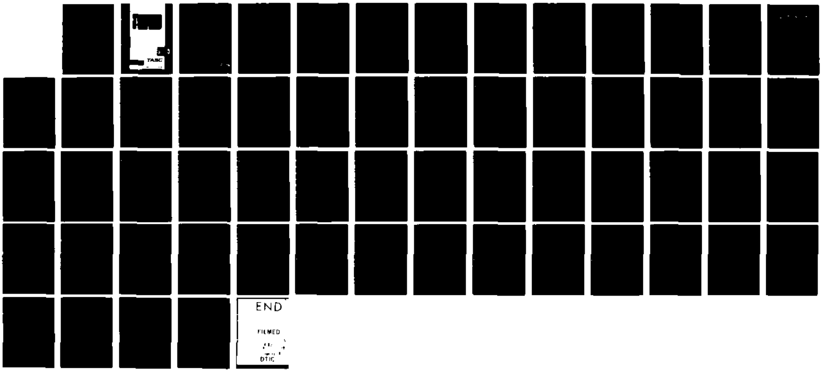

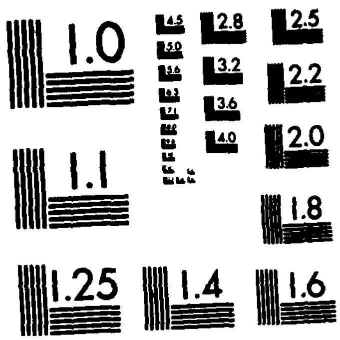

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THE ANALYTIC SCIENCES CORPORATION

TR-3164

MX SYSTEMS STUDY FINAL REPORT

30 November 1982

Prepared under:

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for

BALLISTIC MISSILE OFFICE
Department of the Air Force
Norton Air Force Base, California

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FOREWORD

This report documents the results of work performed for the USAF Ballistic Missile Office, under Contract No. F04704-81-C-0003, over the period from 15 January 1981 to 30 September 1982. The focus of the effort reported on herein is the MX Intercontinental Ballistic Missile Full Scale Engineering Development program. Two specific activities were undertaken: development of a methodology for the generation and presentation of guidance system test data (at flight readiness reviews) to enhance the effectiveness of pre-flight guidance accuracy assurance procedures, and an assessment of the potential value of SATRACK to Western Test Range operations. A summary of the results of each of these activities is presented in this report. References 1 and 2 contain the detailed results of these investigations.

The authors wishes to express their appreciation for the technical support provided by Mr. Gary A. Matchett, in the area of SATRACK performance analysis, and the programming support provided by Mr. Roger A. Katz, both of TASC.

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ABSTRACT

This report summarizes the results of two investigations performed in support of the MX Full Scale Engineering Development program. The first investigation focused on alternative ways to present guidance system test data to enhance the effectiveness of preflight accuracy assurance procedures. The attributes of a desirable accuracy assurance system are discussed and the nature of the required structure and contents of such a system in the MX guidance context are defined. A review of the MX guidance production test structure is presented from which potential traceability parameters are then identified. Methods for relating production test results to traceability parameters are established and preliminary recommendations made concerning the contents and organization of a test traceability presentation format intended for use in flight readiness reviews.

The second investigation addressed the potential value of the SATRACK range instrumentation system to MX testing on the Western Test Range. Mathematical models describing the errors associated with the MX guidance system, the SATRACK system, and the environmental factors that affect system performance were developed. Particular attention was paid to the gravitational and ionospheric delay errors. The models were used, in an error covariance simulation, to project SATRACK performance. The value of SATRACK in assessing the inflight performance of the MX Guidance System under both baseline and larger-than-anticipated error conditions was addressed. The use of signature analysis to isolate errors to a particular instrument was also investigated. A number of GPS based instrumentation alternatives were also postulated. Recommendations related to the value of instrumentation based on GPS and specific mechanization recommendation resulted from this investigation.

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1. INTRODUCTION

This report summarizes the results of activities performed in support of the MX Full Scale Engineering Development (FSED) program ongoing at the USAF Ballistic Missile Office (BMO). The areas of investigation are:

- Development of a data presentation format that will enhance the effectiveness of pre-flight accuracy assurance procedures
- Assessment of the performance potential associated with the use of SATRACK* on the Western Test Range.

Final results and recommendations associated with each of these activities are presented herein. References 1 and 2 contain the details of each of these investigations.

1.1 BACKGROUND

Requirements associated with MX Intercontinental Ballistic Missile (ICBM) testing will have a significant impact on weapon system test methodology and on associated range instrumentation. For example, the MX Inertial Guidance System is required to be autonomously self-aligning before launch. Alignment accuracy under these conditions is a sensitive function of the performance of the inertial sensors prior to launch, at which time this performance is subject to loose monitoring

*SATRACK is the SAtellite TRACKing system developed by the US Navy to support the Submarine Launched Ballistic Missile (SLBM) flight test program.

only. As a result, preflight accuracy assurance must be based on data collected during factory testing, at the instrument and system levels, and the inferences that may be drawn from this data concerning inertial sensor performance at the time of launch. This information, along with data developed by the guidance system's inertial instruments during system calibration and alignment, will be the only data available to support the preflight accuracy assurance decision making process. Costs associated with the missile, guidance system, range instrumentation and other flight test elements make accuracy assurance a critical consideration during the preflight portion of each missile launch. The purpose of the work reported on here is the development of an improved system for test data selection, processing and presentation in support of accuracy assurance activities. This work, referred to herein as the MX guidance test traceability effort, is focused on the development of a methodology that will improve the MX guidance accuracy assurance process.

The MX guidance system has been designed to provide a reduction in the guidance system contribution to weapon CEP as compared to Minuteman III. The accuracy goal is beyond that which is measurable by the existing Western Test Range uprange and midrange radars. Consequently, if guidance system performance during powered flight is to be assessed, a new range instrumentation system must be considered. One such system is the SATRACK system developed by the Navy for testing its Submarine Launched Ballistic Missile (SLBM) system. A SATRACK performance assessment investigation was performed under this contract in order to evaluate the potential of this set of instrumentation for MX guidance system testing.

1.2 REPORT OVERVIEW

1.2.1 MX Guidance Test Traceability

Procedures for conducting Flight Readiness Reviews (FRRs) are currently under development for the MX guidance system. To a large extent they are being developed along the lines of the procedures used in the Minuteman flight test program. While they are being designed to use test data acquired during the testing of the instruments and subsystems that comprise a candidate guidance system, they are perceived to suffer from certain limitations. For example:

- No indicators are included that portray the constraints on acceptability established by mission performance requirements
- Subassembly tests are not, in general, being exploited to yield pertinent system performance information
- No apparent attempt is made to establish "traceability parameters" whose behavior can be tracked from test-to-test.

The objective of the MX Guidance Test Traceability activity, reported on herein, is to enhance the effectiveness of pre-flight guidance accuracy assurance procedures. One vehicle for this enhancement is an improved decision support format for presenting guidance system accuracy parameter test history data at flight readiness evaluations. The required attributes of this data presentation system are:

- All relevant historical accuracy test data for the guidance system under consideration should be included in the presentation format

- The presentation format must be designed for ease of data assimilation and interpretation
- The format must highlight critical accuracy anomalies that threaten the attainment of flight test objectives
- The format must allow easy incorporation of specific test results.

The nature and contents of a data presentation system meeting these requirements are discussed in this report.

1.2.2 SATRACK Performance Assessment

A number of alternative range instrumentation systems, with capabilities superior to the existing Western Test Range radars, have been proposed for use in support of MX guidance system testing. One of these, SATRACK, is an instrumentation system developed specifically for ballistic missile accuracy evaluation. SATRACK was developed by APL to support the Navy's Strategic Systems Project Office in meeting the objectives of the TRIDENT I (C4) Improved Accuracy Program. SATRACK is based on the use of Global Positioning System (GPS) signals, received and translated onboard the missile from L-band to S-band, and retransmitted to a ground (or sea) tracking system to be recorded and analyzed after the flight (Ref. 3). Figure 1.2-1 illustrates the concept as it is proposed to be applied to MX. The figure shows the L-band signals from four GPS satellites (more or fewer may be used) being received by an antenna aboard MX, translated to S-band, and retransmitted, via the telemetry antenna, to a ground tracking station. At the ground station, the signals are further demodulated, sampled, and recorded for post-flight processing.

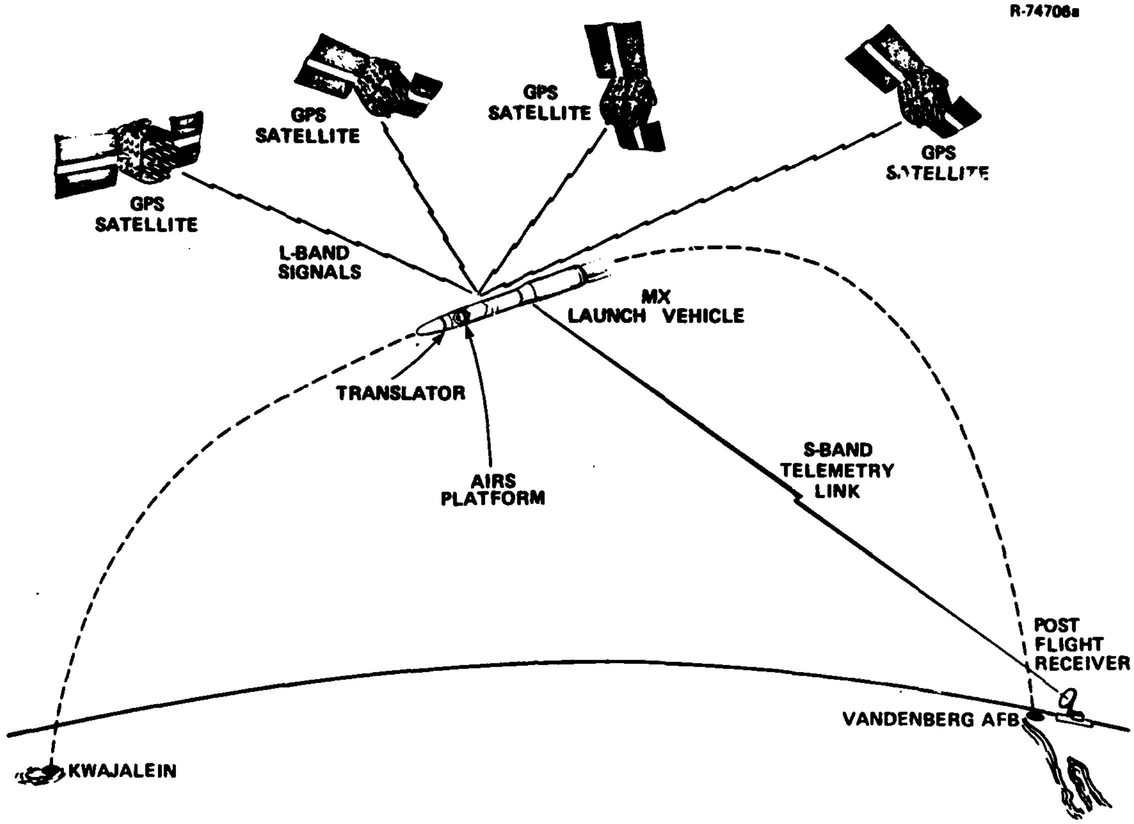

Figure 1.2-1 MX/SATRACK Configuration

During ground processing, the code phases and carrier frequencies of the received GPS signals are measured and compared to one another. By differencing signal characteristics between pairs of GPS satellites, the common downlink signal dynamics are removed, and the differences may be converted into estimates of differences in satellite-to-missile ranges and range-rates. These differences are used to estimate, post mission, the position and velocity of the missile through its powered flight phase of flight.

The goals of the MX/SATRACK performance analysis are:

- Evaluate potential applicability of the SATRACK system to MX/AIRS guidance system testing

- Highlight hardware performance requirements necessary to isolate unique AIRS-related error characteristics
- Assess the impact of residual gravity and ionospheric errors on instrumentation performance
- Address non-accuracy issues associated with implementation of SATRACK on the Western Test Range.

The ability of SATRACK to meet these performance goals is addressed in this report.

1.3 REPORT FORMAT

This report is divided into two segments (Chapters) corresponding to the major areas of activity identified in Section 1.1. Chapter 2 summarizes the traceability effort undertaken in support of the preflight accuracy assurance enhancement activity. Chapter 3 contains the SATRACK performance assessment activity results. Finally, Chapter 4 highlights the principal results of the two areas of investigation, and presents a number of recommendations resulting from these efforts.

2. MX GUIDANCE TEST TRACEABILITY

2.1 INTRODUCTION

The MX Guidance Test Traceability effort was motivated by a need to exploit production test measurements, taken at various levels of assembly of a flight test candidate guidance system, as useful contributors to preflight accuracy assurance evaluations. These evaluations are to be used during flight readiness reviews and launch site operations. The second Technical Operating Report (TOR) for the MX Guidance Test Traceability effort (Ref. 1) was devoted to a definition of preflight accuracy assurance requirements for the MX guidance system, and to the presentation of the results of a review of the production test sequences for that system and its components as potential sources of useful inputs to the preflight accuracy assurance process.

As an introduction to the subject of MX Guidance Test Traceability, the salient results and conclusions of the second Technical Operating Report are repeated here. They fall into three general categories:

- Definition of guidance system errors that are of concern during the preflight calibration/alignment and inflight guidance processes
- Identification of production tests that yield accuracy parameter measurements that can potentially be related to guidance system errors of concern
- Definition of some difficulties encountered in relating the test measurements to preflight guidance system errors.

2.1.1 Guidance System Errors of Concern

Two distinct preflight calibration/alignment sequences exist, one associated with R&D test flights and the other with operational test flights. The latter sequence is subject to time constraints that raise concern over the ability of the cal/align filter to converge to acceptable values for the accuracy parameters that it is designed to estimate. This situation will be aggravated if the initial values for those parameters, at the start of preflight calibration and alignment, assume magnitudes that are at the extremes of the expected distributions built into the cal/align filter.

In both R&D and Operational Calibration and Alignment sequences, the following classes of error are of particular interest as traceability parameters to be included in an accuracy assurance system:

- Uncertainties in the initial values (at the start of preflight Calibration and Alignment) of errors not modeled as active states in the cal/align filter (Initial Uncertainties)
- Operating Instability characteristics of both modeled and unmodeled error sources present in the guidance system
- Error Parameter Shifts in the in-flight environment.

An additional error class of interest in Operational test flights only is:

- Initial Uncertainties of errors modeled as active states in the cal/align filter.

Subsequent developments concern these classes of error only.

2.1.2 Related Production Test Measurements

Potential sources of test data relating to the guidance system errors of concern listed in Section 2.1.1 are identified in Table 2.1-1. This table results from an extensive review of the production test procedures currently proposed for acceptance and quality configuration testing of the MX guidance system and its subassemblies and inertial components.

It should be noted that the data relating to the evaluation of error source initial uncertainties (at the start of the launch site cal/align sequence) is expected to accrue primarily from accuracy parameter changes between tests separated by considerable intervals of time. The time separation (and the common interspersion of environmental events between tests) allows the evaluation of accuracy parameter trends that can be extrapolated with some degree of confidence. Supporting data may come from individual tests that are designed to measure the accuracy parameter change across a particular environmental event. In general, however, it is more difficult to relate these individual test measurements to launch site initial uncertainty with any degree of confidence.

Error source operating instability data, on the other hand, will, of necessity, be derived from analysis of the results of long-term operating stability tests. In such cases it would ideally be desirable to obtain data over continuous test periods of duration comparable to (or longer than) the expected launch site cal/align maintenance duration. Such long test times are objectionable from cost and schedule points of view and some assumptions have to be made (based on design considerations) about the nature of the error processes

TABLE 2.1-1
POTENTIAL SOURCES OF TEST TRACEABILITY DATA

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TRACEABILITY PARAMETER CATEGORY	TRACEABILITY PARAMETER	POTENTIAL SOURCE OF DATA
1. Initial Uncertainty of Unmodelled Error Sources	TGG	
	• Major Compliances (D_{IS}, D_{OS})	• Change in Magnitude from TGG ATP to IMU ATP
		• Shift over Cooldown/Vibration in TGG ATP
	• Minor Compliances (D_{II}, D_{IO}, D_{SS})	• Change in Magnitude from TGG APT to IMU ATP
	• IA Alignment About OA	• Change from TGG ATP to TGG RIT
	• Radial Flotation Error	• Change from TGG ATP to TGG RIT
	• OA Pendulosity	• Change from TGG ATP to TGG RIT
	SFIR	
	• None	
2. Operating Instability	TGG	
	• Lumped D_F, D_I and D_S	• Earth-Fixed Drift Te. in TGG ATP
		• Turn-on and Stability Drift Tests in SFIR RIT
	SFIR	
	• Lumped Bias & Scale Factor	• Five-Day Stability Test in SFIR ATP
		• Overnight/Weekend Stability Drift Test in SFIR RIT
		• Turn-on Drift Test in SFIR ATP
	• Coning Angle (γ_C)	• Five-Day Stability Test in SFIR ATP
3. Shifts in the Operating Environment		No Specific Sources of Data in the Production Test Sequences
4. Initial Uncertainty of Modelled Error Sources	TGG	
	• D_F, D_I and D_S	• Changes in Magnitude Across Entire Test Sequence
		• Partial Values from TGG ATP, TGG RIT, IMU ATP and IMU RIT
	• D_0	• Change in Magnitude from TGG ATP to IMU ATP/RIT to MGCS ATP to MGCS C/A
		• Partial Value from IMU ATP/RIT
	• Torque Scale Factor	• Change in Magnitude from TGG RIT to IMU ATP/RIT to MGCS ATP to MGCS C/A
		• Partial Value from IMU ATP/RIT
	SFIR	
	• Bias (B)	• Changes in Magnitude Across Entire Test Sequence
		• Partial Values from SFIR ATP, SFIR RIT and IMU ATP/RIT
	• Scale Factor (SF)	• Changes in Magnitude Across Entire Test Sequence
		• Partial Values from SFIR ATP, SFIR RIT and IMU ATP/RIT
	• Coning Angle (γ_C)	• Changes in Magnitude Across Entire Test Sequence
		• Partial Values from SFIR ATP and IMU ATP/RIT
	• Cross-Axis Non-Linearity (FX1)	• Changes in Magnitude Across Tests Other Than SFIR RIT
		• Partial Values from IMU ATP/RIT and MGCS ATP

KEY: TGG = Third Generation Gyro; SFIR = Specific Force Integrating Receiver
IMU = Inertial Measurement Unit; MGCS = MX Guidance System
ATP = Acceptance Test (Procedure); RIT = Receiving Inspection Test;
C/A = Calibration/Alignment

characterizing inertial instrument performance in order to utilize the data acquired from the shorter tests that are used in practice.

Finally, it should be noted that no useful sources of measurement data relating to accuracy parameter changes in the flight environment have been identified in the production test sequences. Information on such environmentally-induced changes will presumably be acquired from high stress characterization tests on representative engineering test models of the guidance system and its components. This information does <u>not</u> qualify for inclusion in a test traceability system which, by definition, must rely on production test results.

2.1.3 Relating Test Measurements to Preflight Guidance System Errors

This is the central problem to be solved in defining a guidance test traceability system of value for preflight accuracy assurance. In essence, it is the converse of the problem of determining acceptance test tolerances for instrument, subsystem and system tests from an error budget that describes the expected guidance system error behavior during a defined flight test sequence (incorporating preflight cal/align processes). Unfortunately, factors other than the allowable (error budget) value of the error source under consideration enter into the last steps of the process used to determine acceptance test tolerances. In any endeavor to construct the converse process (relating past production test results to preflight guidance system errors), these factors appear at the starting point of the development, frequently with complicating consequences.

For example, supposing the initial uncertainty of a gyro major compliance drift coefficient at launch is the guidance system error under consideration. An error budget value for this parameter will be established from consideration of its effect on guidance system flight accuracy in the presence of all other expected guidance system errors. This value forms a nominal starting point for the design of lower-level-of-assembly acceptance tests that involve measurements of major compliance coefficients. It can be quickly recognized that, at the gyro test level, any attempt to directly evaluate the initial uncertainty of major compliance coefficients at launch would entail unacceptably long acceptance test times and test costs. It would involve observations of the stability patterns of those coefficients over periods of time and events comparable to those experienced by the gyro between the last production test measurement of the coefficients (during IMU acceptance test) and launch. Periods of several months duration and a multiplicity of events such as cooldowns, storage, transportation and handling and operation for varying lengths of time could well characterize this portion of the gyro's life history. Thus, the designer of instrument-level acceptance tests is forced into a compromise between test comprehensiveness and test brevity. For the parameters under consideration (major compliance drift coefficients) the compromise has taken the form of conducting simple D_{IS}, D_{OS} magnitude measurements at the gyro acceptance test level. Of themselves, these measurements provide essentially zero information on the expected initial uncertainty of compliance drift at launch. Instead, they establish whether or not the gyro under test conforms to family design type characteristics in the magnitude of its compliance drift coefficients. Conformance is regarded as adequate grounds for acceptance of the instrument.

In a test traceability structure, the result of this single test is unrelatable to expected flight performance unless some link is established between the magnitude of compliance drift coefficients and their variability over the period between last preflight calibration and flight. However, subsequent tests (at the IMU and guidance system level) are conducted in the production test sequence in which the compliance drift coefficients are re-evaluated. To the extent that the intervening environment between tests can be related to the environment experienced between last calibration and launch, the test-to-test changes in compliance coefficients can be used as results pertaining to the expected value of initial uncertainty at launch. In addition, during IMU Acceptance Testing, the changes in these coefficients over one cooldown and over one exposure to vibration (for workmanship integrity checking) are also measured. These tests also yield data of potential use to a test traceability system and, once again, the problem is that of relating the test environment to the events expected to occur between the last determination of major compliance coefficients before launch and the launch itself.

The MX guidance production test structure is replete with examples that resemble the above case but with secondary variations. Those variations occur in three principal areas:

- The events expected to occur between the last parameter calibration and launch operations
- The nature of specific tests conducted to establish parameter changes across an environmental event
- The nature of the compromise reached to expedite lower-level-of-assembly testing. In some cases it is recognized that a performance parameter measurement taken

with the instrument outside the IMU is not relatable to its behavior in the IMU environment, either because of test stand orientation stability problems or because of the necessity of using an instrument in an electronic environment that does not resemble that of the IMU. In such cases it appears that wide tolerances are used for the parameter magnitude limits in instrument acceptance tests (i.e., test noise is recognized as a dominating influence) in the interest of minimizing false rejections. In such instances, the utility of the production test data to a test traceability system is even further subjugated to test pragmatism.

In all cases, the central problem is the same - that of relating the test environment to the events occurring between last parameter calibration and launch site operations. In many cases a secondary problem exists - that of allowing for justifiably coarse measurements at lower levels of assembly.

The above observations relate specifically to the problems encountered in setting up a test traceability system based on the use of results from existing production tests to provide assurance that guidance system error initial uncertainties are within acceptable limits at the launch site. A similar assurance is required that the operating instability characteristics of the inertial instruments will allow satisfactory guidance system calibration and alignment prior to launch.

In this matter, a basic assumption is necessary - that instrument operating instability characteristics are repeatable across intervening events once the instrument has reached stable operating conditions. (For example, a gyro exhibits the same random drift characteristics at operating temperature

before and after a cooldown, even though its bias drift levels may have changed as a result of the cooldown). Any variation in operating instability characteristics that results from routine environmental events during the prelaunch history of an inertial instrument (e.g., cooldown and restoration to operating temperature) will constitute "anomalous" behavior that is <u>not</u> amenable to evaluation from currently scheduled production tests. Such "anomalous" behavior cannot, therefore, be incorporated in a test traceability system based on existing production test procedures. Examples of such anomalous drift behavior do occur in the FSED Third Generation Gyros (TGGs) as they are currently designed. However, a successful test traceability system will require either solution of this drift anomaly problem by instrument redesign, adequate statistical characterization of the drift anomalies and their relation to environmental events (and a correspondingly modified production test structure) or the design and use of an anomaly detection algorithm in the prelaunch calibration and alignment filters.

Given the independence of inertial instrument operating instability characteristics from routine prelaunch environmental events, the remaining problem is that of creating a link between measurements of operating instability collected at the instrument test level and guidance system alignment accuracy during the cal/align maintenance (or continuous calibration) mode of operation that precedes launch. Two salient difficulties have to be overcome in creating this link:

- Identification and correct accounting for test noise (test stand seismic motions, effects of operationally non-representative test configurations, etc) present during instrument testing

- Adequate representation of the spectral characteristics of operating instability and their effects on guidance system flight accuracy.

The following section (2.2) is devoted to a discussion of possible solutions to the problems outlined above. Section 2.3 describes the type of test traceability system that would evolve from those solutions.

2.2 SUGGESTED SOLUTIONS

2.2.1 Error Initial Uncertainties

The solution proposed to the problem of estimating probable guidance system error initial uncertainties at the launch site from previously acquired production test data can take two forms, depending on the completeness of the records of system, subsystem and inertial instrument history available from the MX Data Management System (DMS). In the ideal case,* a complete record would be available that identified and dated every significant event experienced by the instruments, subsystems and guidance system up to the time of the final accuracy assurance review. In this context, "significant" events include:

- Date at which a performance parameter was last measured, test method and test result

*The other extreme situation involves no recorded and dated events being available from the DMS. In this worst case, statistically representative "Event Models" have to be developed to permit initial uncertainty predictions. In that this approach introduces additional prediction uncertainties and the DMS is expected to contain event/date information, only the ideal case is pursued herein. An analogous development would apply in the worst case.

- Number of subsequent environmental events broken down by type (power cycles, exposure to vibration, transportation, installation in a higher assembly).

In addition, some reasonable estimate of environmental events (in particular power-downs) still scheduled to occur before the start of final preflight calibration and alignment should be available. Under these ideal circumstances, an explicit estimate of an error source initial uncertainty would take the form:

$$\widehat{IU}_{T_{L/CA}} = MU \oplus f_1(t)\ (T_{L/CA} - T_M) \oplus f_2(n_c)N_c \oplus f_3(n_v)N_v \oplus f_4(n_I)N_I \qquad (2.2\text{-}1)$$

where

$\widehat{IU}_{T_{L/CA}}$ = Estimated error initial uncertainty at launch or start of preflight calibration and alignment

MU = Measurement uncertainty at last measurement of the magnitude of the error

$f_1(t)$ = Error growth as a function of elapsed time in a defined mixed (part dormant, part operating) quiescent environment

$T_{L/CA}$ = Time of launch or commencement of preflight calibration and alignment

T_M = Time of last measurement of the magnitude of the error

$f_2(n_c)$ = Error growth as a function of number of power cycles (to a cooled condition)

N_c = Number of power cycles since last measurement of magnitude of the error

$f_3(n_v)$ = Error growth as a function of number of vibration cycles experienced by the equipment

N_V = Number of vibration cycles between last measurement of error and launch or start of preflight calibration and alignment

$f_4(n_I)$ = Error growth as a function of number of installations into a higher assembly

N_I = Number of installations between last error measurement and launch or start of preflight calibration/alignment.

and the symbol $\oplus$ indicates RSS summation.

In general, the functions $f_2(n_c)$, $f_3(n_v)$ and $f_4(n_I)$ are expected to be subject to a further decomposition of the form:

$$f_i(n_j) = \sigma_{\Delta\varepsilon j}\, f(n_j) \tag{2.2-2}$$

where

$\sigma_{\Delta\varepsilon j}$ = Standard deviation of change in error parameter across one event of type j (power-down, vibration, installation)

$f(n_j)$ = A mathematical function of n_j only.

In many cases, production tests are conducted to measure $\sigma_{\Delta\varepsilon j}$ for specific error parameters across specific, single-shot events. (For example, one test in the TGG Acceptance Test procedure provides measurements of the changes in a lumped drift quantity across sequential cooldowns. See Table 4.1-1 of Ref. 1). In other cases magnitude measurements of a specific parameter are made at different points in the test sequence and the intervening elapsed time and environmental experiences are definable from the DMS. (For example, the magnitudes of the fixed gyro drift (D_F) and the unbalance drift (D_I, D_O, D_S) coefficients are measured in four or five different tests in the production test sequence. See Table 4.1-1 of Ref. (1).)

In principle, the results of such sequences of measurements can also be processed to yield values for $\sigma_{\Delta\varepsilon j}$ provided that:

- An event of type j occurs in at least three of the periods between tests
- The instrument under test is a member of the statistical class whose error characteristics contributed to the determination of the functions $f(n_j)$.

The residual problem is the determination of $f(n_j)$ for each error parameter of interest and each type of environmental event (j). This type of information can come only from an adequate instrument error characterization program that results in the adoption of suitable error models for the instruments. If such error models are not established, or if they lack credibility and applicability to each instrument of the affected design class, then the task of establishing a meaningful test traceability system (which is an exercise in prediction) will be intractible. In the subsequent development it will be assumed that the functions $f(n_j)$ can be adequately determined from characterization test data.

At this point some categorization of different types of $f(n_j)$ will help to clarify the discussion. The categories of interest are "strong", "moderate" and "weak" functions. A typical "strong" function is $f(n_j) = n_j$, which implies that the error considered increases linearly with each successive occurrence of the event j. (For example, if the standard deviation of the change in a gyro drift over a single cooldown is $\sigma_{\Delta D}$, then the standard deviation over four cooldowns is $4\sigma_{\Delta D}$. This implies a unit positive correlation between changes occurring over successive cooldowns.) A typical "moderate" function is $f(n_j) = \sqrt{n_j}$ which implies complete randomness (zero correlation) in error parameter behavior across successive

events of the type j. A typical "weak" function is $f(n_j) = 1$ which implies that a negative correlation exists between changes occurring over successive cooldowns such that the standard deviation of error magnitude ($\phi_{\varepsilon\Delta j}$) does not vary with n_j;

It is to be expected that a number of weak functions will appear in the matrix of error parameters and environmental events of interest in setting up a test traceability system. Also, there will probably be combinations of error parameter and environmental event in which $\sigma_{\varepsilon\Delta j}$ is demonstrably negligible, and situations in which the last measurement of an error parameter occurs close to the start of preflight calibration and alignment and no environmental event (except the passage of time) takes place in the intervening period. All of these occurrences will lead to simplification of the general methodology outlined here.

A possible complicating factor may be the importance of environmental events, other than those defined in Eq. 2.2-1, that are not easily definable from the DMS records. For example, storage attitude relative to the gravity vector (which may affect error characteristics during subsequent use) and shocks experienced during transportation and handling. At the present time it is difficult to assess the importance of such events from available data on the sensitivity of the instruments to the events and their likelihood of occurrence.

Finally, the question of imperfect error parameter test measurements (test noise) has to be addressed. In the production test sequence, not all measurements of a given error parameter are of equal value, owing to (usually unavoidable) variations in test accuracy at different levels of test. Thus, some measures of confidence levels associated with different

tests must be built into the test traceability system to avoid placing undue weight on an unprecise measurement in the final accuracy assurance decision process. On the somewhat simplistic assumptions that the error parameter itself and the test process errors can be represented as independent, normally-distributed random variables, it should be sufficient to compute weighting factors of the form:

$$W_i = \frac{\sigma'^2_{\Delta\varepsilon j}}{\sigma'^2_{\Delta\varepsilon j} + \sigma'^2_{TNi}} \qquad (2.2\text{-}3)$$

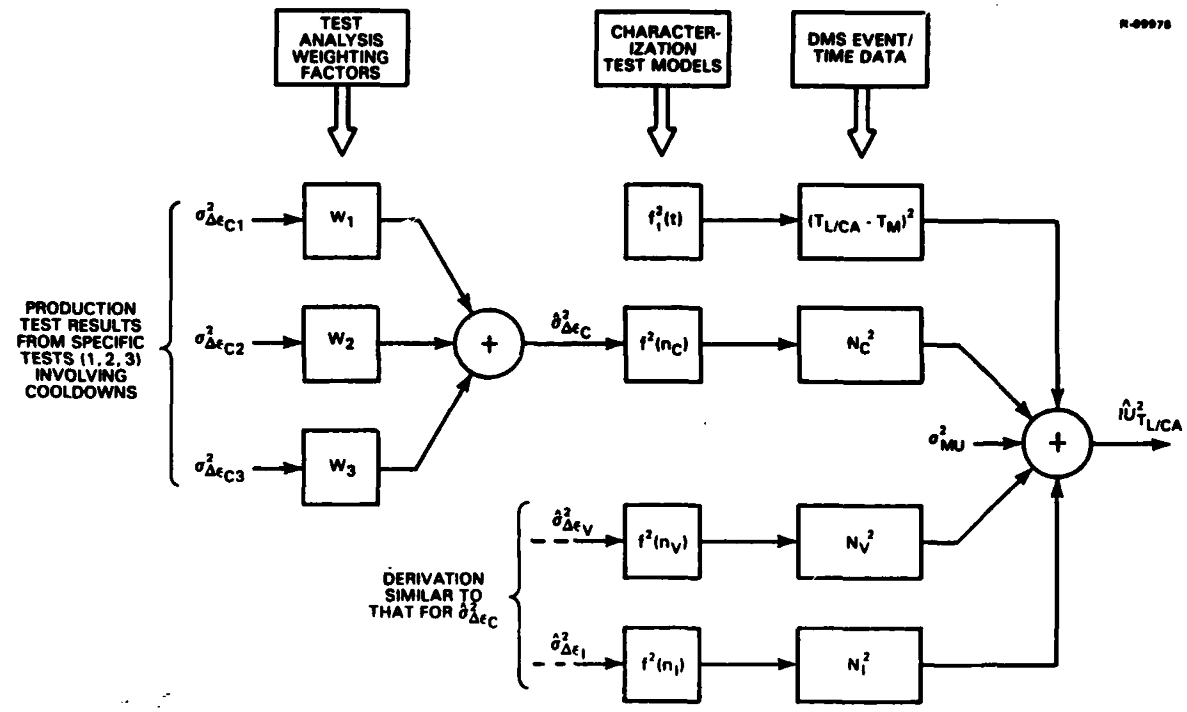
through analysis of each test conducted, where:

$\sigma'_{\Delta\varepsilon j}$ = Expected standard deviation of change of error parameter across event j

σ'_{TNi} = Expected standard deviation of test noise error for test i.

These weighting factors should be used to modify the values of $\sigma_{\Delta\varepsilon j}$ obtained from the test measurements before using them in Eq. 2.2-1.

A diagrammatic representation of the process just described is shown in Fig. 2.2-1 for one error parameter and for the particular situation in which production test results are obtained from sequences of closely-spaced (in time) tests designed to measure $\sigma_{\Delta\varepsilon j}$ for specific environmental events. In the equally common situation in which the magnitude of an error parameter is measured at points widely separated in time with more than one environmental event occurring in the interval between measurements, the manipulation required to form the estimates $\sigma^2_{\Delta\varepsilon j}$ is somewhat more complicated and also somewhat more reliant on the availability of good characterization test models. However, the principle remains the same. The exact



NOTE: $W_i = \dfrac{\sigma'^2_{\Delta\epsilon j}}{\sigma'^2_{\Delta\epsilon j} + \sigma'^2_{TNi}}$ WHERE $\sigma'_{\Delta\epsilon j}$ = EXPECTED STANDARD DEVIATION OF ERROR PARAMETER CHANGE ACROSS EVENT j

σ'_{TNi} = EXPECTED STANDARD DEVIATION OF TEST NOISE ERROR FOR TEST i

Figure 2.2-1 Scheme for Estimation of Error Parameter Initial Uncertainty

problem formulation depends on the nature of the events occurring between the two measurements. It is to be expected that some indeterminate situations will arise, because of the existing test structure, that preclude the formulation of any useful inputs to the initial uncertainty estimation process from the available test data.

The further use of the error initial uncertainty estimates in a test traceability presentation format is described in Section 2.3 of this report.

2.2.2 Operating Instability Errors

To incorporate measurements of inertial instrument operating instability errors into the test traceability system it is necessary to establish a link between those measurements and IMU alignment accuracy during the cal/align maintenance (or continuous calibration) mode of operation that precedes launch. This involves defining sets of "traceability parameters" which can be:

(a) Evaluated from production test measurements

(b) Related to IMU alignment accuracy.

Fortunately, it is both feasible and economically acceptable to conduct production tests on the inertial instruments that are designed to measure their operating instability characteristics in a one-g field and in orientations relative to the gravity vector that are similar to those experienced during the cal/align maintenance and/or continuous calibration modes of system operation. The overnight/weekend stability drift tests of the TGG Receiving Inspection Test sequence and the Five Day SFIR Stability Test of the SFIR Factory Acceptance Test are typical examples.

It is also possible (either through time domain uncertainty analysis (Ref. 4) or through spectral analysis) to analyze the data acquired during these tests in such a way as to determine the spectral content of operating instability errors in terms of a number of superimposed random processes of mathematically describable form. If a sufficient number of random process types is used to model the operating instability characteristics of the general class of instrument involved, then any set of test results from a given instrument of that

general class should be representable as a linear combination of the modeled random processes. Figure 2.2-2 illustrates this concept graphically. In the figure, the solid curve represents the result of processing long-term stability test measurement data for one instrument to form a two-sample Allan variance(1) plot (Green chart - see Ref. 2). The solid straight lines each represent the Allan variance(1) of one random process of a reference model for the general class of instruments. In the postulated case the reference model is assumed to contain four distinct random processes - quantization noise, white noise, random walk and time-ramp processes.

It can quickly be seen, by inspection of Fig. 2.2-2 that the instrument test data (in the fictitious example shown) is represented by a curve that falls below the reference model at all points. That is, the actual instrument is assumed to exhibit better stability characteristics, under test, than the reference model in all parts of the pertinent frequency spectrum. Assuming that the reference model is a reliable representation of random processes actually present in the general class of instruments (and, to a greater or lesser extent in any individual instrument that is a member of that class), it is now possible to do two things:

(1) Synthesize an instrument operating instability characteristic from the random processes used to define the reference model

(2) Relate the various segments of the synthesized characteristic to those of the reference model in terms of relative magnitude.

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(1)Note: Actually, the square root of the Allan variance is plotted against averaging time to form a Green chart.

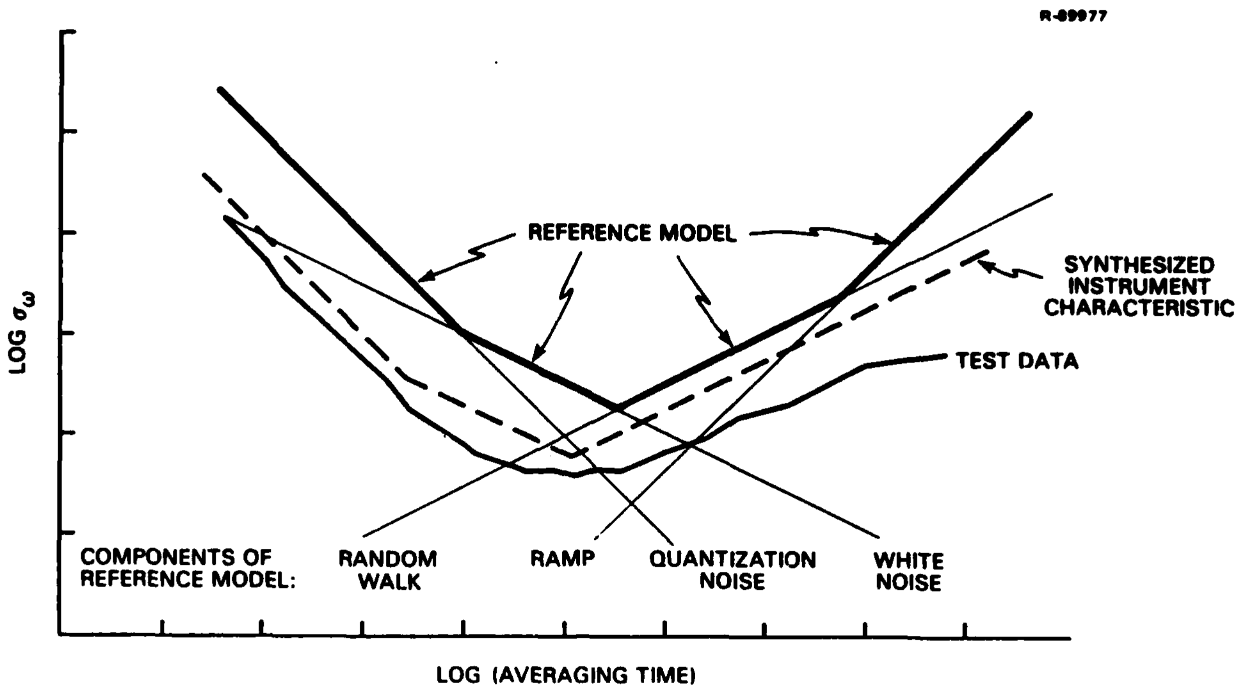

Figure 2.2-2 Sample Green Chart

The synthesized instrument characteristic is shown as the broken-line, segmented curve in Fig. 2.2-2. It is deliberately chosen to match (but to lie slightly above) the measurement data curve and to retain the characteristic "Green chart" slopes of the random processes constituting the reference model. From this curve it can be conservatively estimated that the test data contains quantization noise, white noise and random walk processes, but to a degree less than those exhibited by the reference model in all cases. In alternative terms, the operating instability characteristics of the instrument tested can be conservatively represented by the mathematical description of the synthesized characteristic:

$$OI = K_1(QN_R) + K_2(WN_R) + K_3(RW_R) + K_4(R_R) \tag{2.2-4}$$

where

QN_R = Reference model quantization noise value

WN_R = Reference model white noise value

RW_R = Reference model random walk value

R_R = Reference model ramp value.

and $K_1 < 1$, $K_2 < 1$, $K_3 < 1$, $K_4 = 0$ in the fictitious example shown.

The values of K_1, K_2, K_3 and K_4 can be numerically determined from the Green chart and therefore satisfy the first criterion for "traceability parameters" - they can be evaluated from production test measurements. They also satisfy the second criterion of being relatable to IMU alignment accuracy during the cal/align maintenance (or continuous calibration) mode of operation that precedes launch. It is, for example, a simple matter to determine (via computer-based covariance analysis) the effect of any of the component random processes of the reference model on IMU alignment accuracy, provided that the mechanization of the cal/align maintenance (or continuous calibration) mode is known. (In fact it is normal to use a reference model composed of error budget values for its constituent random processes, in which case these computations will have already been performed). Then, (since inertial system error propagation during the cal/align maintenance mode is describable by linear equations and the principle of superposition holds) the effect of components of the synthesized instrument characteristic on IMU alignment accuracy can be determined by simple scaling:

$$\sigma(\text{Alignment Error})_{i(SIC)} = K_i \sigma(\text{Alignment Error})_{i(REF)} \quad (2.2\text{-}5)$$

where

K_i are the coefficient values determined from the green chart

SIC refers to the synthesized instrument characteristic

REF refers to the reference model.

Thus the coefficients, K_i, form natural "traceability parameters" for use in the process of relating instrument operating instability production test measurements to preflight accuracy predictions.

In practice there are certain limitations inherent in the test measurement methods that must be taken into account when constructing a test traceability system along the lines suggested above. These are discussed below under the general headings of Test Time and Test Noise.

<u>Test Time</u>: Long-term stability tests, scheduled as part of the production test sequences for the SFIR and TGG, currently extend over periods of several days duration. The confidence levels associated with low-frequency (correlation time comparable to test duration) random process determination from test data are low under these circumstances. The test data is probably adequate to support flight-readiness determinations for R&D test flights in which the duration of the cal/align maintenance mode will not exceed 48 hrs. It is less than satisfactory for the support of flight-readiness determination for operational test flights in which the continuous calibration mode may extend for 30 days. Since the only solutions to this problem lie in either extended instrument production test times or the acquisition of instrument error characterization data that establishes a link between long-term (30 day) and

short-term (~3 day) instabilities, further comment at this point is of little value until more test experience is available.

Test Noise: Instrument tests are conducted under environmental circumstances that are not representative of those encountered by the instruments when installed in an IMU. In general, these non-representative environments introduce noise into the test measurements that can be misinterpreted as part of the instrument instability characteristic. In some ways this situation is analogous to the test noise problem discussed in connection with the determination of error parameter initial uncertainties in Section 2.2.1 of this report. However, there is a significant difference in the way in which operating instability test noise must be handled. The difference arises because there is usually only one type of test employed for the measurement of operating instability characteristics, and it is usually conducted once only in the production test process. The technique of weighting independent test results to form an error parameter estimate, that was used in estimating initial uncertainty from a number of observations, is not applicable here. Instead, some methods are required for directly evaluating the probable contributions of the test environment to the test results and removing them before using the test data as described earlier.

Without a great deal of test site survey data from the locations at which TGIIs are to be acceptance tested, and without some common test station certification standards for electronic equipment stability in the presence of power supply and temperature variations, it is difficult to comment on the degree of success that might be attainable in this endeavour. Results reported in Ref. 3 indicate that, at currently acceptable levels of TGII stability performance, some test environmental effects

can be discounted or allowed for by direct computation. In the former category are quantization noise effects introduced by operating TGGs in torque-to-balance loops for drift test purposes. There is no a priori reason to expect quantization noise to be part of the TGG drift operating instability characteristic when it is used as part of a platform stabilization loop in the AIRS IMU. Thus, it is safe to assume that any quantization noise appearing in the Green chart plot of TGG drift obtained from long-term instrument stability tests is a feature of the test configuration and not of the instrument. In the latter category, the effects of earth tides on the outputs of SFIR long-term stability tests can be computed with the aid of lunar-solar ephemeris data and compensated for by subtraction from the raw data before further processing.

However, a number of potential sources of test noise are less amenable to evaluation, notably seismic motions in the vicinity of the test stand (particularly angular motions) and local environmental effects attributable to the specific test electronics and temperature control equipment used.

Considerable discrepancies exist between models proposed to describe the rotational motions of a test pad arising from seismic effects. For example, rotational motions consistent with the model proposed in Ref. 6 would constitute a serious obstacle to the evaluation, through single instrument testing, of the components of TGG drift operating instability to levels compatible with MX guidance system alignment objectives. On the other hand, the two test sites listed in Ref. 5 are characterized by seismic motion models that appear to be sufficiently quiet to allow meaningful gyro random drift analyses from single instrument test data over frequency ranges covering all but the longer-period (~30 days) effects. <u>A need exists for further data, specific to the sites at which TGG</u>

production acceptance testing is to be conducted, in order to determine the utility of single instrument operating instability test data acquired at those sites.

The issue of test electronics as a noise contributor also raises some difficult questions. The instruments can only operate in conjunction with support electronics and the operating instability error sources of direct interest are, in reality, the instruments coupled with the electronics used to support them in the assembled IMU. At the instrument test level, therefore, it is necessary to provide test electronics that either accurately emulate the IMU electronics or are so much more deterministic than the IMU electronics in their effects on instrument behavior that they can be ignored as a source of operating instability errors. Neither of these requirements is easily achieved. Accurate emulation of the IMU electronics is greatly complicated by the totally different physical environments occupied by the instrument during acceptance testing and operation in the IMU. On the other hand, the provision of "noise-free" test electronics involves extensive design, certification and standards control processes that are difficult to justify when it is considered that this approach yields data on the instrument only, and not on the instrument-IMU electronics combination.

Some test techniques have been proposed for relief from the test pad motion and test electronics noise problems discussed above. The most notable of these is simultaneous testing of pairs or triplets of instruments in configurations (usually "back-to-back") that permit compensation of the test data for common mode effects attributable to test set-up imperfections. This is probably an effective approach in evaluating the higher frequency components of instrument operating instability where the probability of correlation between the

errors of two instruments over the test duration if low. It is probably less effective in the low-frequency domain where, for example, the probability of encountering two gyros with unacceptable drift ramps of similar magnitude and polarity is large enough to be of concern.

The alternative is to recognize instrument acceptance testing as a source of traceability data that is incomplete (for the reasons discussed above) and requires corroboration from IMU or system level testing. Occasional opportunities for such corroboration do appear in the production test sequence. One example is provided by the use of Kalman filters to estimate individual gyro drift coefficients during the absolute azimuth verification portion of the IMU Acceptance Test and composite gyro drift coefficients during the guidance system cal/align maintenance mode of operation. In both of these operations the IMU stable member attitude trajectory is the same as that which precedes launch. On the assumption that the effects of filter mismodeling are minimal, the drift coefficient estimates can be regarded as test data points in a record of gyro fixed-attitude drift versus time and processed via the use of the Green chart methodology to identify the components of the drift operating instability characteristic. In this situation the high-frequency components ($f > \frac{1}{2(\text{Kalman filter iteration time})}$) of drift instability will be missing from the results but, when combined with the results of instrument back-to-back testing, they should provide a reasonably complete picture of TGG drift operating instability characteristics. Finally, it should be observed that the exercise of this option during the guidance system cal/align maintenance mode would require on-line data processing at the launch site and resembles real-time accuracy diagnosis rather than test traceability.

The further use of the operating instability "traceability parameters" (coefficients, k_i, from Eq. 2.2-4) in a test traceability presentation format is described in Section 2.3 of this report.

2.3 TEST TRACEABILITY PRESENTATION FORMAT

The attributes required of a test traceability data presentation system were enumerated and briefly described in Section 1.2 of this report. They included such diverse requirements as comprehensiveness (i.e., inclusion of all relevant accuracy test data), ease of assimilation and interpretation and highlighting of critical anomalies that threaten flight test accuracy objectives. The recommended presentation format was developed through consideration of this last requirement as a starting point.

ICBM flight test accuracy objectives are usually described in terms of the Circular Error Probable (CEP) of target area impact errors for a large ensemble of flights. The nominal CEP is computed from a complete system error budget that consists of expected values for all error sources in the system that contribute significantly to impact error. The desired result of a flight test is either an impact at a distance from the target that is comparable to the radius of the nominal CEP or the collection of evidence leading to explicit identification of reasons for failure to achieve this objective. Thus, the nominal impact CEP serves as a yardstick against which flight test performance is measured.

In the absence of test measurement data that provides pre-flight observability of the actual magnitude of error sources listed in the error budget, the nominal CEP is also

the predicted CEP for any flight test candidate system. However, should pre-flight test measurements indicate that any given error budget term actually has a non-nominal value in a flight test candidate system, then the predicted CEP for that system will differ from the nominal CEP by an amount which can be easily calculated. This difference, denoted by $\Delta(\text{CEP})_i$ for error budget quantity i, is the most direct way of depicting the impact of a measured deviation of an error source from its error budget value on the probable outcome of the impending test flight. The extension of this procedure to include actual test measurements of larger numbers of error budget terms involves no new principles. Summation of the individual $\Delta(\text{CEP})_i$ values then results in a projected $\Delta(\text{CEP})_{\text{total}}$ for the candidate guidance system which is a simple, direct measure of predicted flight performance embodying all available test measurement data.

To highlight critical anomalies and to provide direct visibility into the composition of $\Delta(\text{CEP})_{\text{total}}$, a test traceability presentation format based on this concept should retain, at least, the first level of diagnostic information in the form of a listing of the individual $\Delta(\text{CEP})_i$ contributions. In addition, there appears to be some benefit to focussing attention on anomalous error values emanating from the test data. Even though their contributions to $\Delta(\text{CEP})_{\text{total}}$ may not be large, sizeable anomalies in the test data results may indicate potential problem areas that could have a bearing on flight readiness decisions.

A tabular version of a traceability data presentation format that incorporates the information described above is shown in Fig. 2.3-1. This format is presented to indicate how the error initial uncertainty estimates (Section 2.2.1) and operating instability "traceability parameters" (Section 2.2.2) are used in the end product. Graphical presentations embodying

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ERROR CATEGORY	INSTRUMENT	ERROR PARAMETER (i)	WEIGHTED TEST VALUE ($\widehat{IU}_{TL/LA}$) ERROR BUDGET VALUE	$\Delta(CEP)_i$
Initial Uncertainty	TGG1	D_F	1.5	+0.02
		D_I	0.5	-0.10
		D_S	-	-
		D_{IS}	-	-
		.	-	-
		.	-	-
		.	-	-
	SFIR1	B	-	-
		SF	-	-
		γ_c	-	-
		FX1	-	-
	TGG2	D_F	-	-
		D_I	-	-
	SFIR3	B	-	-
		SF	-	-
		γ_c	-	-
		FX1	-	-
			PROJECTED $\Delta(CEP)_{IU}$	---

Figure 2.3-1 Tabular Traceability Presentation Format: Initial Uncertainty Impacts

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ERROR CATEGORY	INSTRUMENT	ERROR PARAMETER (i)	TRACEABILITY PARAMETER VALUE (k_i)*	$\Delta(CEP)_i$
Operating Instability	TGG1	Lumped Drift:		
		WN	2.5	+0.10
		RW	0.2	-0.12
		Ramp	-	-
	SFIR1	Lumped Bias and Scale Factor:		
		QN	-	-
		WN	-	-
		RW	-	-
		Ramp	-	-
	TGG2	Lumped Drift:		
		WN	-	-
	SFIR3	Lumped Bias and Scale Factor:		
		QN	-	-
		WN	-	-
		RW	-	-
		Ramp	-	-
			PROJECTED $\Delta(CEP)_{OI}$	---
			PROJECTED $\Delta(CEP)_{TOTAL}$	---

$^*k_i = \dfrac{\text{Test Value}}{\text{Error Budget Value}}$ when the reference model used is the error budget Model.

Figure 2.3-1 Tabular Traceability Presentation Format (Continued): Operating Instability Impacts

the same essential data are possible and may provide improved visual impact and quicker recognition of problem areas. However, it is suggested that temptations to incorporate additional information into the basic presentation format be resisted in the interest of providing a complete, but easily

digestible, overall picture of flight test accuracy predictions. Further detail on critical anomalies identifiable from the basic format rightly belongs in supplementary worksheets that trace the derivation of the related entries from the available test data.

2.4 SUMMARY

Starting from a definition of the categories of error of concern during preparation of an MX guidance system for flight test, a logical structure has been developed for incorporating production test measurements into a summary presentation format for use during pre-flight accuracy assurance reviews. Some difficulties inherent in the use of data from existing production tests have been discussed and possible methods for minimizing those difficulties listed. A recommended presentation format embodying all the requirements of a test traceability summary presentation has been described.

3. SATRACK PERFORMANCE ASSESSMENT

The results of the MX/SATRACK performance evaluation are presented here in four parts.

- Baseline Performance Results, showing the limited value of SATRACK if the AIRS platform performs as expected
- Sensitivity Studies, showing that improvements in any one of the four disturbing error groups, associated with the instrumentation and environment, will not dramatically improve system performance
- Recovery of Larger than Anticipated Instrument Errors, showing that SATRACK has significant potential for use in off-nominal situations
- Signature Analysis, showing likely error identification and isolation capability under some assumed conditions.

3.1 BASELINE PERFORMANCE RESULTS

One way to quantify the performance of the SATRACK instrumentation system is through recovery ratios. Each AIRS error parameter has a initial uncertainty (standard deviation) resulting from preflight calibration and alignment. The SATRACK system measurements, during flight, serve to add additional information about the error parameters and reduce the uncertainties. The ratio of the post flight uncertainty to the preflight uncertainty is known as the recovery ratio.

An alternate way to present the results, chosen for use in this report, is to work in terms of miss uncertainty. The uncertainty in a single parameter, or the correlated uncertainties in any group of parameters, will cause a corresponding uncertainty in target miss. By working in terms of miss uncertainties, the varying importance of the individual error parameters are automatically taken into account, the problem of varying units is eliminated, and composite results for groups of parameters may be presented, all of which contribute to both improved and quicker understanding of the results obtained.

SATRACK measurements during boost (and especially post boost) will sharply reduce the total uncertainty in where the missile will land, but will not be able to assign this improved overall knowledge to individual error parameters. Thus, a major effect of the SATRACK measurements will be to strongly correlate the error parameters, especially in the miss domain, not to reduce the uncertainties of individual error parameters (or the corresponding miss uncertainty from individual error parameters). Thus, the total miss uncertainty with SATRACK measurements might be smaller than the uncertainty due only to a single error parameter or to a small group of parameters.

Since SATRACK measurements after boost do little or nothing to recover inertial system errors that arise during boost, the simulations in this study were terminated shortly after boost. At this point the overall miss uncertainty is still fairly large. Were the simulations to be continued, the overall miss uncertainty would fall dramatically, but the miss uncertainties due to small groups of AIRS error parameters would not be reduced further.

Table 3.1-1 presents the baseline performance projections of the MX/SATRACK system in terms of miss uncertainties. The columns labeled "without SATRACK" apply to the preflight uncertainties, while the columns labeled "with SATRACK" apply to post flight uncertainties assuming nominal SATRACK performance. The downrange (DR) and crossrange (CR) columns have been normalized by the correlated total downrange and crossrange miss respectively. The 60 individual error parameters have been gathered into 11 groups. A comparison of the without and with SATRACK column in the table shows, if the AIRS system is operating within current expectations, that SATRACK will do little with regard to calibration of the inertial measurement unit instrument errors. Only the two largest sources of error will be measured to significantly better than their preflight values. Initial platform alignment uncertainty

TABLE 3.1-1

BASELINE PERFORMANCE PROJECTION IN TERMS OF NORMALIZED DOWNRANGE AND CROSSRANGE MISS

ERROR GROUP		WITHOUT SATRACK		WITH SATRACK	
		DR	CR	DR	CR
Initial	Position	0.11	0.01	0.11	0.01
	Velocity	0.19	0.05	0.19	0.04
	Alignment	0.02	0.95	0.02	0.35
SFIR	Bias	0.01	0.01	0.01	0.01
	Scale Factor	0.02	0.01	0.02	0.01
	Nonlinearity	0.18	0.04	0.18	0.04
	Misalignment	0.01	0.00	0.01	0.00
	Float Cocking	0.96	0.26	0.68	0.24
TGG	Bias Drift	0.00	0.02	0.00	0.02
	Mass Unbalance	0.00	0.06	0.00	0.06
	Compliance	0.01	0.18	0.01	0.17
Correlated Totals		1.00	1.00	0.70	0.28

(almost totally azimuth alignment uncertainty) will be reduced to about 35% of its preflight value. Miss uncertainty due to SFIR float cocking effects (a combination of six terms) will be reduced to about 68% of the preflight value. Virtually no added information will be provided about any other error parameter.

3.2 SENSITIVITY STUDIES

There are four major groups of errors that interfere with SATRACK's ability to determine AIRS parameters: gravitational modeling errors, ionospheric delay errors, receiver tracking errors, and GPS satellite ephemeris and clock errors. It is of considerable interest to see how improvements in any one of these four groups might improve SATRACK performance. Table 3.2-1 summarizes the effects of totally eliminating errors from each of the four groups while leaving the remaining three at their nominal values. It shows that the SATRACK disturbing errors are fairly well balanced among the four groups, and that improvements in any one area will not strongly improve the overall system.

3.3 RECOVERY OF LARGER THAN ANTICIPATED INSTRUMENT ERRORS

While SATRACK might not be able to reduce AIRS parameter uncertainties much below their budgeted values, it could well provide a good measure of off-nominal performance and identify abnormal error conditions. Five simulation runs were made to investigate this possibility. Table 3.3-1 summarizes these runs. In each case, a particular error or group of errors was simulated to be larger than nominal, and the miss

TABLE 3.2-1

BASELINE SATRACK SENSITIVITY TO DISTURBING ERRORS IN TERMS OF NORMALIZED DOWNRANGE AND CROSSRANGE MISS

ERROR GROUP		BASELINE		NO GRAVITATIONAL ERRORS		NO IONOSPHERIC ERRORS		NO RECEIVER ERRORS		NO GPS SATELLITE ERRORS	
		DR	CR	DR	CR	DR	CR	DR	CR	DR	CR
Initial	Position	0.11	0.01	0.11	0.01	0.10	0.01	0.11	0.01	0.11	0.01
	Velocity	0.19	0.04	0.19	0.04	0.19	0.04	0.17	0.03	0.18	0.04
	Alignment	0.02	0.35	0.02	0.29	0.02	0.34	0.02	0.29	0.02	0.35
SFIR	Bias	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Scale Factor	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01
	Nonlinearity	0.18	0.04	0.18	0.04	0.18	0.04	0.18	0.04	0.18	0.04
	Misalignment	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00
	Float Cocking	0.68	0.24	0.63	0.24	0.56	0.24	0.54	0.23	0.65	0.24
TGG	Bias Drift	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02
	Mass Unbalance	0.00	0.06	0.00	0.06	0.00	0.06	0.00	0.06	0.00	0.06
	Compliance	0.01	0.17	0.01	0.17	0.01	0.17	0.01	0.15	0.01	0.17
Correlated Totals		0.70	0.28	0.64	0.14	0.58	0.27	0.55	0.19	0.66	0.27

TABLE 3.3-1
SATRACK RECOVERY OF LARGER THAN ANTICIPATED INSTRUMENT ERRORS

ABNORMAL ERROR CONDITION	NORMALIZED MISS UNCERTAINTIES	
	DR	CR
Initial Azimuth Misalignment = 3 × SPEC	0.44	0.13
SFIR Input Axis Misalignment = 10 × SPEC	0.45	0.60
SFIR Nonlinearities 3 × SPEC	0.48	0.52
SFIR Float Cocking Errors 3 × SPEC	0.53	0.81
Gyro Compliances 3 × SPEC	0.57	0.59

uncertainties (due to that error or group alone) are presented, normalized by the downrange and crossrange contribution to miss of each error groups of interest.

As expected, the ability of SATRACK to identify initial platform azimuth misalignment, demonstrated in the baseline results, remains about as strong in absolute terms even if the azimuth uncertainty is increased to three times its nominal value. Also, in agreement with the baseline results is the ability of SATRACK to identify float cocking effects. Shown here, but not noted in the baseline results, is the ability of SATRACK to isolate (to some degree) larger than nominal errors in SFIR input axis misalignments and nonlinearities and in TGG compliances.

3.4 SIGNATURE ANALYSIS

A basic concern relative to any MX test instrumentation system is its ability to detect and isolate errors. The Kalman filter data processing approach shared by SATRACK and other measurement systems is an optimal method of error estimation, but it sometimes fails to provide adequate insight into its own behavior. Error signature analysis is a simpler, graphical method of understanding error detection and isolation that is sometimes capable of giving good insight into the workings of the filtering process, and it does so in the present case.

The signatures appropriate to the SATRACK system are the MX velocity error signatures in AIRS platform coordinates. There is one signature (with three axes) of 54 error parameters. The signatures are collected in Appendix C of Ref. 2. As the appendix describes, the signatures are plotted for an amount of each error that would produce 100 ft of radial (two axis) target miss along the simulated trajectory. These signatures show how velocity errors grow during the boost phase. They are partitioned into seven groups of "look-alike" error signatures.

To relate the error signatures to the measurement capability of the SATRACK instrumentation, a special simulation run was made. This run utilized post flight smoothing of the MX velocity state during boost to show how accurately SATRACK could determine velocity error. The result of this special simulation run is summarized in Fig. 3.4-1. It may be compared to the signatures of Appendix C. Such a comparison shows that should a <u>single</u> AIRS parameter error exist that causes 100 ft or more of target miss, then the SATRACK system could likely isolate that error to one of the seven groups of signatures of the appendix. If the error were to cause somewhat

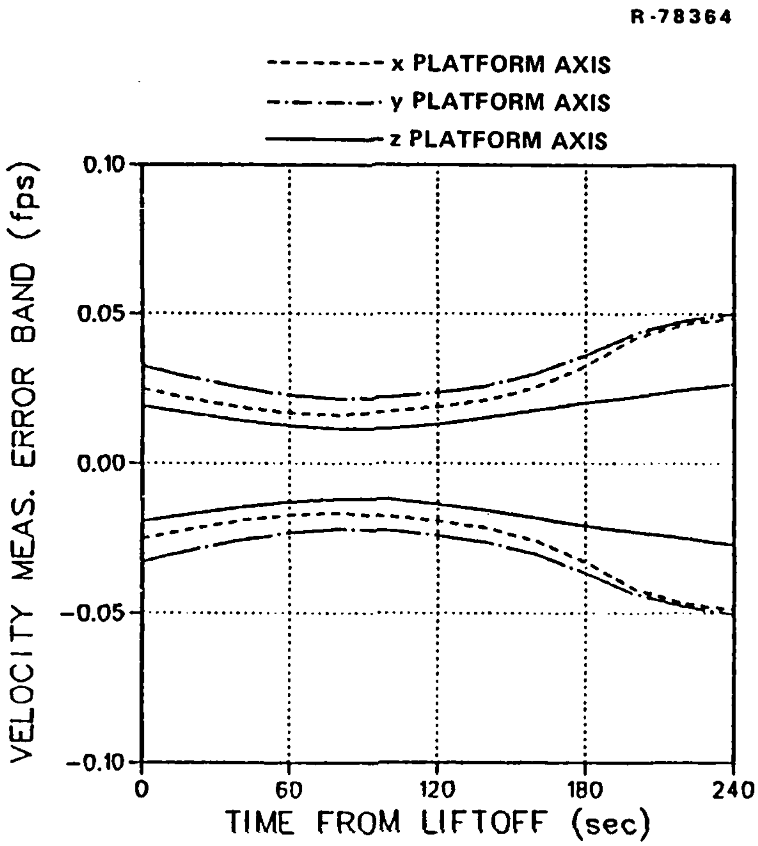

Figure 3.4-1 SATRACK Error Signature Measurement Capability

more than 100 ft of miss, or the SATRACK system were to perform somewhat better than anticipated, then a further isolation might be possible. Figure 3.4-2 shows a possible isolation into one of 12 groups. Isolation beyond this level is unlikely for any reasonable error size (less than 500 ft).

The 54 error parameters used in the signature analysis are not primitive errors. That is, if some off nominal condition were to exist in the AIRS it would likely cause deviations in several of the error parameters, not just in one. Several simultaneous errors are, in general, not so easy to identify and isolate as is a single error. But the seven major signature groups break down along instrument lines, with all errors from a single instrument looking much alike. A significant

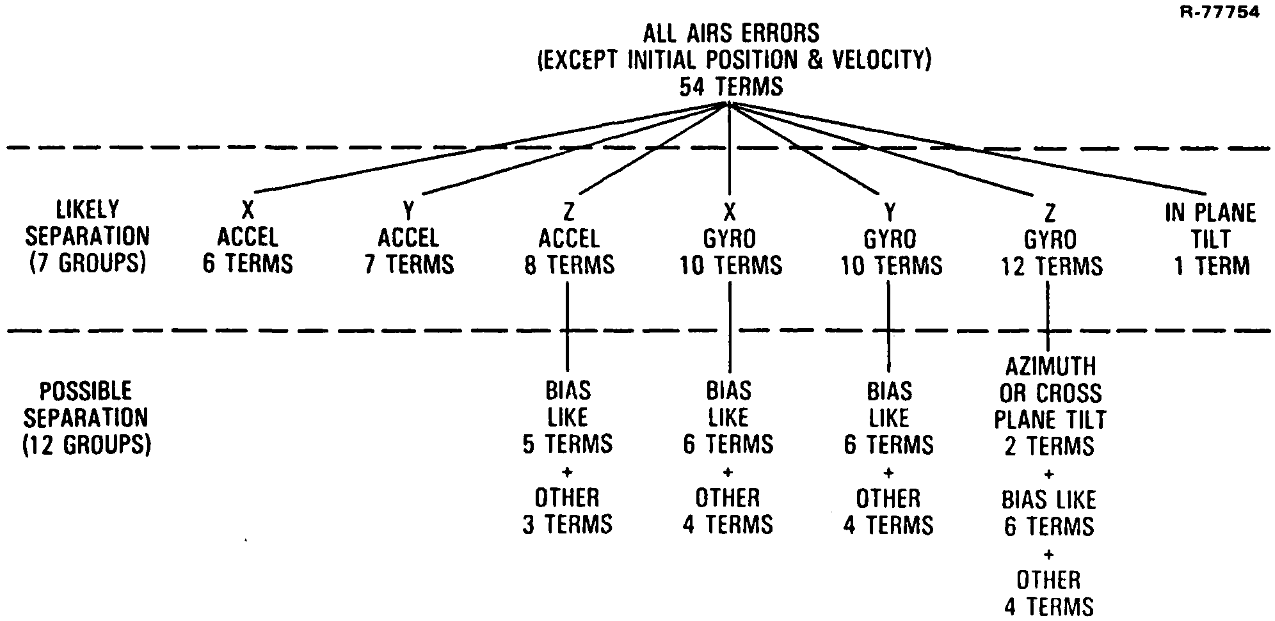

Figure 3.4-2 SATRACK AIRS Error Isolation

number of primitive error sources in the AIRS would confine errors to a single instrument, and in this case the instrument involved could likely be isolated by SATRACK.

3.5 SUMMARY

Based on a detailed model of the MX/SATRACK system and the associated environmental error contributors, the following conclusion has been developed relative to SATRACK performance capability as MX test instrumentation. SATRACK, although not useful in testing AIRS systems that function near their projected accuracy, would be of significant value in the analysis of AIRS performance under severly degraded condition. In particular, isolation of errors to a specific gyro/accelerometer is a capability not achievable using radar based test data, but one which could be realized with use of SATRACK measurements.

4. SUMMARY

This report summarizes the results of two investigations performed by TASC in support of the USAF Ballistic Missile Office under Contract No. F04704-81-C-0003. The investigations focused on the MX Full Scale Engineering Development program. The specific areas of activity are:

- Development of a data presentation format that will enhance the effectiveness of pre-flight accuracy assurance procedures
- Assessment of the performance potential associated with the use of SATRACK on the Western Test Range.

The following sections present the principal results and recommendations that result from these two investigations.

4.1 MX GUIDANCE TEST TRACEABILITY

Two classes of guidance system errors that are of particular concern in the MX guidance system preflight initialization process have been identified. They are:

(1) Uncertainties in the initial values of specific inertial sensor errors at the start of the prelaunch calibration and alignment process (Inertial Uncertainty Errors)

(2) Inertial sensor operating instability errors active during the prelaunch guidance system cal/align maintenance process.

A review of the production test sequences currently required on FSED MX guidance systems, subsystems and inertial sensors has been conducted, resulting in the identification of tests that provide measurement data contributing to the evaluation of the above error types for test flight candidate systems.

Procedures have been defined for relating test measurements to errors of interest. These procedures have been designed to allow for the observability-limiting effects of test imperfections at various test locations and for the influence on error initial uncertainties of environmental events occurring between specific tests and the start of the prelaunch calibration and alignment process.

A test traceability data presentation format has been defined for use as a preflight accuracy assurance data summary during flight readiness reviews and launch site operations. The format is designed to incorporate all test measurements related to the two important error types taken during the production test sequence on the flight candidate guidance system and its constituent subassemblies and inertial components. The utility of the data presentation format as a launch decision guide is enhanced by relating all entries to changes in predicted impact CEP and by summing all the individual contributors to form a predicted total impact CEP change.

Difficulties inherent in relating the results of existing production tests to errors at the launch site have been discussed at some length and, where possible, suggestions made for changes in test methods to provide improved error prediction confidence levels.

4.2 MX/SATRACK PERFORMANCE ASSESSMENT

Major conclusions to be drawn from the performance analysis of SATRACK, as applied to MX testing, are:

- If the AIRS IMU performs as expected, then SATRACK will provide improved information only about initial azimuth misalignment and SFIR float cocking effects
- Of the four major groups of disturbing effects (gravitational modeling errors, ionospheric errors, GPS satellite ephemeris and clock errors, and SATRACK receiver tracking errors) no one effect is of overriding importance. Improvements in any one of these areas will not dramatically improve SATRACK performance
- The GPS two-frequency ionospheric compensation technique that could be added to SATRACK is not likely to be of significant value, especially in the time frame of interest (1983-1985), since a minimum in the sunspot cycle minimizes ionospheric delays
- SATRACK instrumentation can be quite valuable in assessing larger than expected AIRS errors. Several specific examples simulated show SATRACK is able to isolate errors at two to three times specification
- Signature analysis considerations confirm and explain the ability of SATRACK to detect and isolate AIRS errors. A single AIRS parameter error that would cause 100 ft of radial miss along the simulated trajectory would almost surely be detected and isolated into one of seven groups of errors. The groups of look-alike (and, hence, inseparable) errors follow instrument lines, so a single error could likely be isolated to a specific instrument

- The error isolation capability of SATRACK results from good doppler measurement ability coupled with good measurement geometry. This combination is not likely to be achieved by any other means on the Western Test Range.

Table 4.2-1 compares five instrumentation alternatives for MX testing relative to a number of issues. Several of these issues are not pertinent to a radar tracking system, but are pertinent to the four GPS-based schemes. The "R/PA on MX" column refers to a GPS receiver aboard the missile, as in the MAE Project. SATRACK I and SATRACK II differ in that SATRACK II has two-frequency ionospheric compensation and a good GPS receiving antenna aboard MX. The good antenna is very valuable, but the two-frequency operation is of limited value. The column labeled "TRANSLATOR + GND R/PA" refers to a translator scheme similar to SATRACK, but with a real time receiver at the ground station. This last alternative might offer cost and operational advantages over SATRACK, but would have signal handling limitations and potential dropout problems. The issue labeled "risk" refers to being able to construct an instrumentation system that will offer usable performance. Given potential radar geometry in the Western Test Range, it seems unlikely that radar measurements will be useful for MX performance assessment and error recovery. The higher accuracy estimate for the onboard receiver comes from the P-code capability and two-frequency operation of this unit. This system was not simulated and might not (in practice) be substantially more accurate than SATRACK.

TABLE 4.2-1

MX INSTRUMENTATION CONFIGURATION ALTERNATIVES

ISSUES	SYSTEM					COMMENTS
	RADAR ONLY	R/PA ON MX	SATRACK I	SATRACK II	TRANSLATOR + GND R/PA	
Realtime Receiver	-	Yes	No	No	Yes	Could be added to SATRACK
Adequate Antenna on MX	-	Yes	?	Yes	Yes	Recommended
Dual Frequency Ionospheric Compensation	-	Yes	No	Yes	Option	Not recommended (Traditional approach)
Handle More Than 4 Satellites	-	No	Yes	Yes	?	Some added accuracy
Signal Droupouts	Sometimes	Infreq?	Freq.	Infreq.	?	Post flight receiver has best flexibility
Geometry	Poor	Good	Good	Good	Good	Good over limited periods until '86-'87, when it becomes uniformly good
IOC Date	Now	?	'83	'85-'87	?	
Cost	Lowest	Highest	Low	Medium	?	
Risk	High	Low	Low	Low	Medium	
Accuracy	Low	High?	Medium	Medium	Medium	

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